PREDICTING THE ARRIVAL TIMES OF SOLAR PARTICLES

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ABSTRACT

A procedure has been developed to generate a computerized time-intensity profile of the solar proton intensity expected at the earth after the occurrence of a significant solar flare on the sun. This procedure is a combination of many pieces of independent research and theoretical results. Many of the concepts used were first reported by Smart and Shea (1979) and are summarized by Smart and Shea (1985). Extracts from the general procedure that relate to predicting the expected onset time and time of maximum at the earth after the occurrence of a solar flare are presented.

1. CONCEPTS INVOLVED

Solar energetic particles are assumed to be accelerated in solar active regions from the available coronal material during solar flare events. After the initial acceleration there may be further acceleration of the energetic particle population that interacts with shocks, but these subjects are beyond the scope of this paper. The X-ray, radio and optical emissions during the solar flare event are the indicators (perhaps secondary manifestations) that proton acceleration is occurring. The solar protons emitted from the inner solar corona at a "favorable" position may intercept the earth. In organizing solar energetic ion data it is very useful to use the gross features of the interplanetary magnetic field topology illustrated in Figure 1 (see Roelof; 1973, 1975, 1976; Roelof and Krimigis, 1973; Reinhard et al., 1986) which is determined by the solar wind outflow and the rotation of the sun.

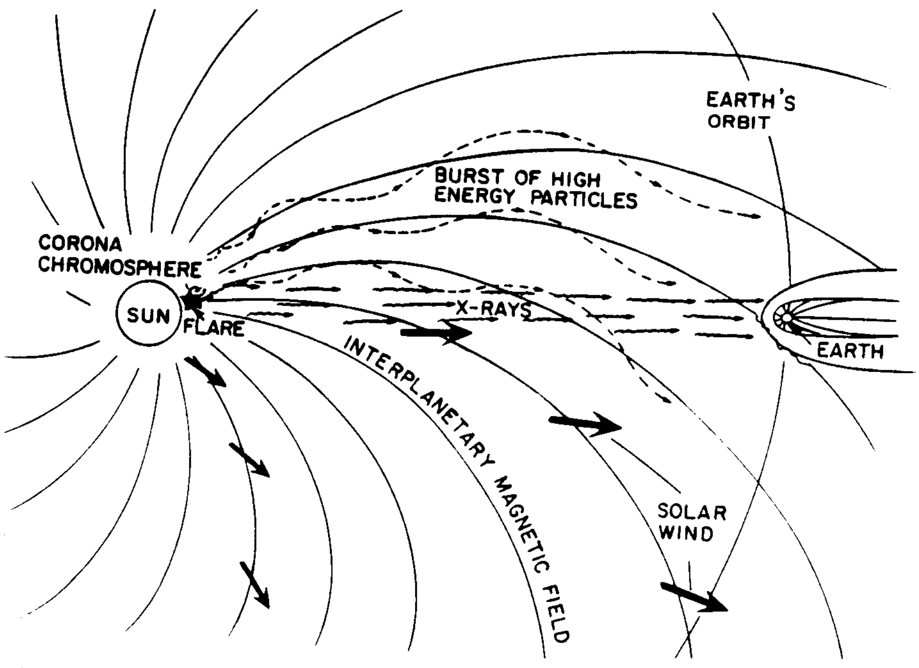

Figure 1. Illustration of the sun and the gross characteristics of the idealized structure of the interplanetary medium.

Once the solar flare accelerated energetic ions arrive at the earth, we can generalize the characteristics of the time-intensity profile observed at any energy above the solar wind domain as illustrated in Figure 2. First there is a propagation delay from the time of the solar flare until the first particles are observed at the earth. After the initial onset of particles, there is a rise in the solar proton flux until a maximum flux is observed, and after the time of the maximum solar proton intensity, there is a slow general exponential decay of the particle flux to background levels. The shape of an individual event may be distorted by features which happen to be present in the interplanetary medium at the time of the solar particle event, and the decay of the solar particle event may be further disturbed by travelling interplanetary shocks, but the general features are always recognizable.

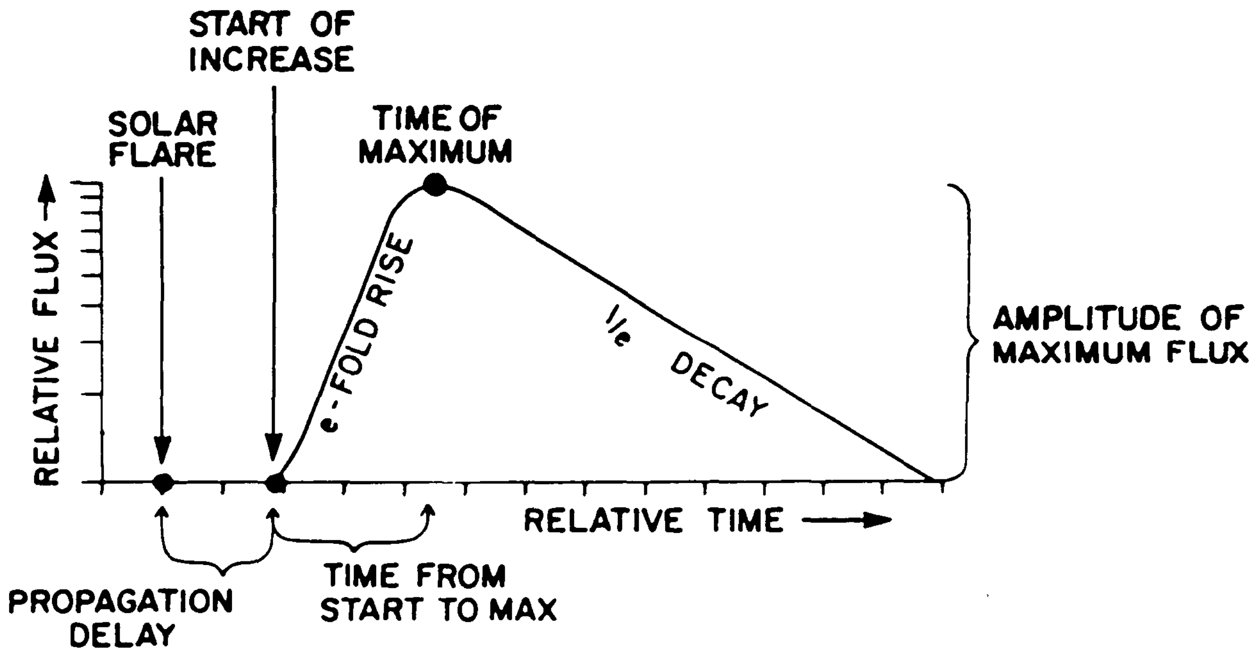

Figure 2. Illustration of the general characteristics of solar proton events.

2. SOLAR PARTICLE PROPAGATION TO THE EARTH

From examining the solar proton data acquired during the past three solar cycles, we can generalize and separate the propagation of solar protons from the flare site to the earth into two distinct and independent phases. The first phase is diffusion from the flare site through the solar corona to the "foot" of the Archimedean spiral path formed by the interplanetary magnetic field line between the sun and the earth. The maximum possible flux is presumed to be at the solar flare site and it is further assumed that there is a gradient in the solar corona extending from the flare site. This gradient attenuates the maximum particle intensity as the angular distance from the flare site increases. The second phase is the propagation in the interplanetary medium from the sun to the earth along the interplanetary magnetic field lines. Both of these phases are illustrated in Figure 3.

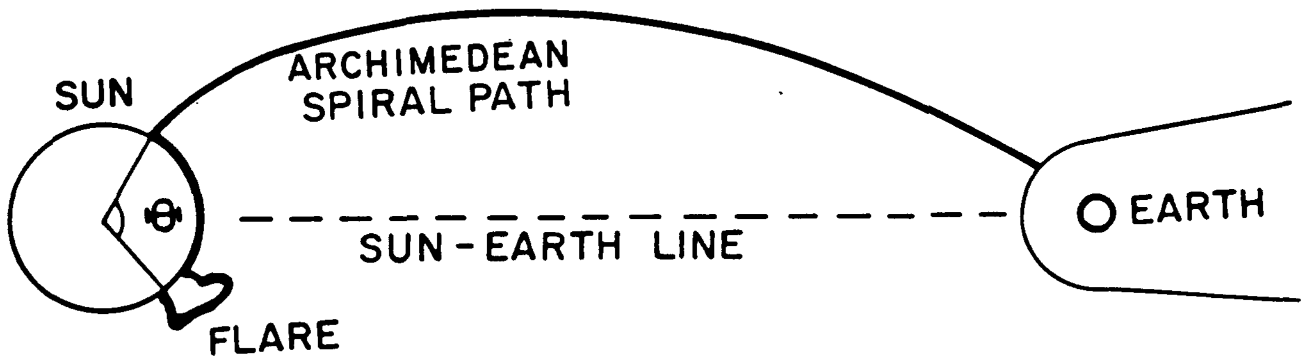

Figure 3. Illustration of the propagation concept. The coronal propagation distance is illustrated by the heavy arc on the sun. Interplanetary propagation proceeds along the interplanetary magnetic field lines which for a constant speed solar wind forms an Archimedean spiral path from the sun to the earth.

2.1 Propagation in the Solar Corona

The concepts we have used for the propagation of solar protons in the solar corona are similar to those originally advanced by Reinhard and Wibberenz (1974). We make very few assumptions as to the manner of coronal transport except that some stochastic processes dominate the particle transport between their source at the flare site and their release point along an interplanetary magnetic field line. In this context we take the fundamental elements of solar particle diffusion theory as developed by early researchers (e.g., Reid, 1964; Axford, 1965; Krimigis, 1965; Burlaga, 1967) and assume that almost all of the major diffusive effects occur in the solar corona. For events observed at the earth, the distance the solar particles travel in the solar corona from the presumed source (i.e. the solar flare site) to the foot of the Archimedean spiral path from the sun to the earth is designated by the symbol Θ.

We assume that coronal propagation is a function of Θ. From diffusion theory we would expect it to be proportional to Θ^2. (See Wibberenz (1974) for a discussion of diffusion theory relating to coronal propagation.) For large values of Θ the propagation delay time to the earth is dominated by the coronal diffusion rather than interplanetary propagation. Some of the early satellite observed data containing onset times of particle events at the earth are those of Barouch et al. (1971), and Lanzerotti (1973); later data sets tend to confirm the general trends noted by the earlier investigators. When these data sets are organized in a heliographic coordinate system they show that the minimum time from the flare onset to particle detection at the earth occurs in a broad range of heliolongitudes around 60 degrees west of central meridian and that the longest times between the associated flare and the onset of particles observed at the earth are for eastern heliolongitude flares.

The distribution of onset times expected for 30 MeV protons for nominal solar wind speeds is shown in Figure 4. The data points shown on the figure are taken from Barouch et al. (1971) and indicate typical variations that may be expected. The minimum in the figure corresponds to a flare at the "foot point" of the Archimedean spiral path between the sun and the earth (57 degrees west of central meridian). To our prejudiced eye, a reasonable fit to the onset data at any specific energy has the functional form of $4\ \Theta^2$.

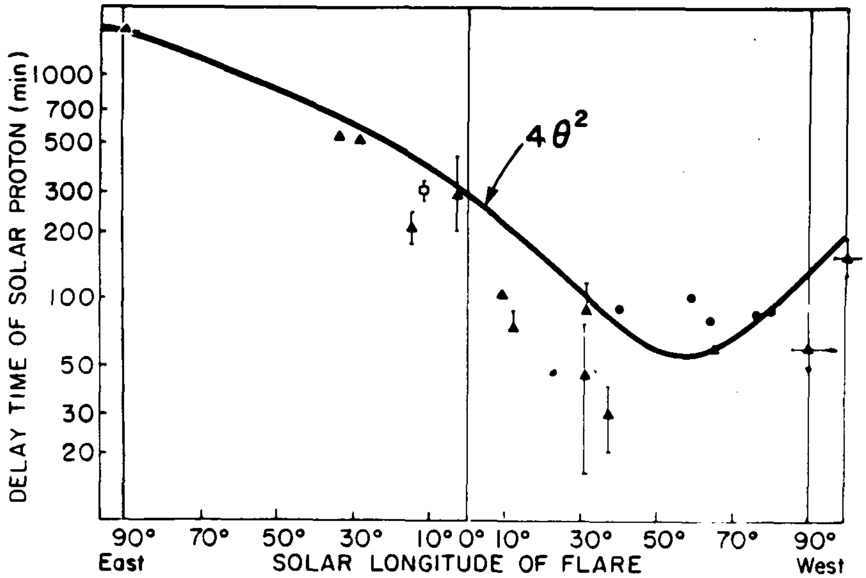

Figure 4. Distribution of onset time of 30 MeV protons observed at the earth as a function of solar longitude. The data points are the measurements of Barouch et al. (1971)

2.2 Propagation in the Interplanetary Medium

After the particles propagate through the solar corona and are released into the interplanetary medium, they essentially propagate along the interplanetary magnetic field lines. During this phase of their propagation we assume that their mean free path length is of the order of 0.1 to 0.3 AU. We make the simplest possible assumptions regarding transport in the interplanetary medium as follows:

a. The particles travel essentially along the interplanetary magnetic field lines with a velocity which is a function of the particle energy.
b. Diffusion perpendicular to the interplanetary magnetic field is assumed to be negligible.
c. The minimum distance to travel from the sun to the earth is the distance along the Archimedean spiral path. The length of the Archimedean spiral path can be obtained by integration of the polar form of the Archimedean spiral equation.

The minimum interplanetary propagation time will be for particles that essentially travel along the interplanetary magnetic field lines with very little scattering, so for scatter free onsets the propagation time from the sun to the earth will be the distance traveled (i.e. the length of the Archimedean spiral path), divided by the particle velocity. After the initial onset it is reasonable to expect that some scattering has taken place and that some aspects of diffusion theory are applicable. The time for the propagation of any specified ion along this path is merely the Archimedean spiral path distance divided by the velocity which is determined by the kinetic energy of the ion. Almost all theories involving differential transport show that the time of maximum is proportional to the square of the distance traveled. (See Wibberenz, 1974.)

The distribution of the observed time of maximum as a function of heliolongitude is illustrated in Figure 5. The data points are from Van Hollebeke et al. (1975) and show the typical range of variations that can be expected. The minimum in the curve corresponds to a flare at the "foot point" of 57 degrees for the Archimedean spiral path between the earth and the sun computed from a nominal solar wind of 404 km/sec. Other data sets (e.g., Reinhard and Wibberenz, 1974) can be plotted in this manner and illustrate the same general characteristics.

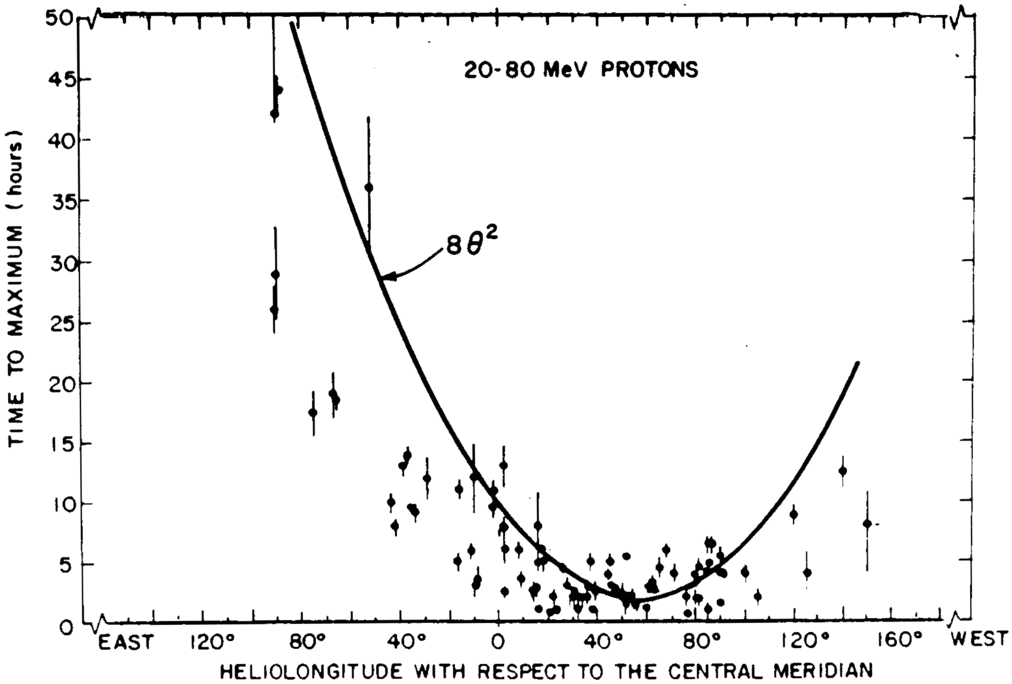

Figure 5. The time from onset to the maximum 20 - 80 MeV proton flux as a function of the heliolongitude of the associated solar flare. The data points are from Van Hollebeke et al. (1975) and the (heavy solid line) is the 8 Θ^2 curve for a nominal solar wind speed.

As a result of diffusion in the solar corona from the flare site to the "foot" of the Archimedean spiral, and the inherent assumption that some stochastic processes are operating, we would expect that there is a solar particle gradient existing in the solar corona such that the proton intensity decreases as a function of distance from the flare site. There is some observational evidence for the existence of such a gradient (Gold et al., 1975; McCracken and Rao, 1970; Roelof et al., 1975; McCracken et al., 1971; Roelof, 1976). The observational evidence suggests that the gradient may vary from case to case. We assume that the gradient from the presumed particle source (i.e. the flare location) to the release point of solar protons observable at the earth (i.e. the "foot" of the Archimedean spiral of the interplanetary magnetic field line between the earth and the sun) is a factor of 10 per radian. Therefore, an observer at one astronomical unit who is connected via the interplanetary magnetic field line to the heliographic longitude of the flaring region would observe the maximum possible particle intensity. An observer whose interplanetary magnetic field connection is at a distance of Θ from the flaring location would observe a flux that has been attenuated by propagation through the coronal gradient over the heliocentric distance in the corona between the flare position and the solar equatorial longitude of the foot point of the Archimedean spiral path from the sun to the earth.

2.3 Event Decay

The decaying portion of the event can be modeled after the principles of collimated convection (Roelof, 1973). After making a number of simplifying assumptions (some of which are that the particle flux can be represented by a simple power law, the anisotropy of the particle flux is small, the magnitude of the interplanetary magnetic field falls off as r^{-2}, and that the particle flux gradient is field aligned and small), a 1/e decay constant can be derived which is a function of the distance along the Archimedean spiral path, the solar wind velocity, and differential energy spectral exponent.

3. HEAVY ION EVENTS

The same principles involved for organizing and estimating the proton (ions with Z=1) arrival and time-intensity profiles are also applicable to heavy ions. These data are conveniently organized by kinetic energy or momentum per unit charge (particle rigidity). It is reasonable to assume that the same principles of coronal propagation and interplanetary propagation apply to all ions independent of the mass or atomic charge. There is a major problem in anticipating the flux or fluence in finding a simple common factor for the elemental abundance ratios. There have been a number of papers reporting the variation of the elemental abundances in solar particle events; see Lin (1987), Mason (1987), and Shea (1987) for recent reviews. A general summary may be that "small" events may have the greatest variability in elemental composition. The elemental abundance ratios seem to have a slight variation according to the energy of the measurement. This may be a reflection of the "size" of the particle event since small particle events would not have many heavy ions at high energies. The hydrogen to helium ratios are the most variable even for "large" events; the heavier elemental abundance ratios seem to be in general agreement with the ratios expected from normal coronal material organized by the first ionization potential. Unfortunately, most of the solar particle data currently available are for protons. So as an expediency, it is required, at least as an interim measure, to estimate the probable heavy ion fluence from the observed or expected proton fluence, except for the relatively few recent cases where the heavy ion flux data have been measured by spacecraft. A table of solar particle element abundance ratios normalized to hydrogen is presented in Table 1.

4. EXTRAORDINARY SOLAR PARTICLE EVENTS

In a discussion of the expected solar particle environment, there is always some discussion of the extraordinary solar particle event or a worst case model. The view of this author is that the extraordinary event, such as the August 1972 sequence of events, is the result of a sequence of occurrences which contribute to the unusually large effect. The 4 August 1972 solar particle event is an outstanding example. This is a sequence of strong converging interplanetary shock structures and a large solar particle event. The extraordinary flux of solar particles observed on 4 August 1972 was the result of a large injection of solar particles from a 3B solar flare at 0413 UT into a region of space where the converging interplanetary shock structures re-accelerated what was a substantial solar particle population into an extraordinary solar particle population. (See Lee (1988) for a more detailed discussion of shock acceleration.) The solar proton time-intensity history of early August 1972 is shown in Figure 6. The results expected from the principles described earlier in this paper are illustrated by the thick gray lines in the figure. It is worth noting that after the interplanetary shock had moved beyond the orbit of the earth, late on 5 August, the event followed our model quite well. The extraordinary flux and extraordinary hard spectrum are present only during the time when the earth is between the two converging interplanetary shocks which are re-accelerating the particle population. This time period, from about 05 UT to about 20 UT, is illustrated by the shaded portion of Figure 6.

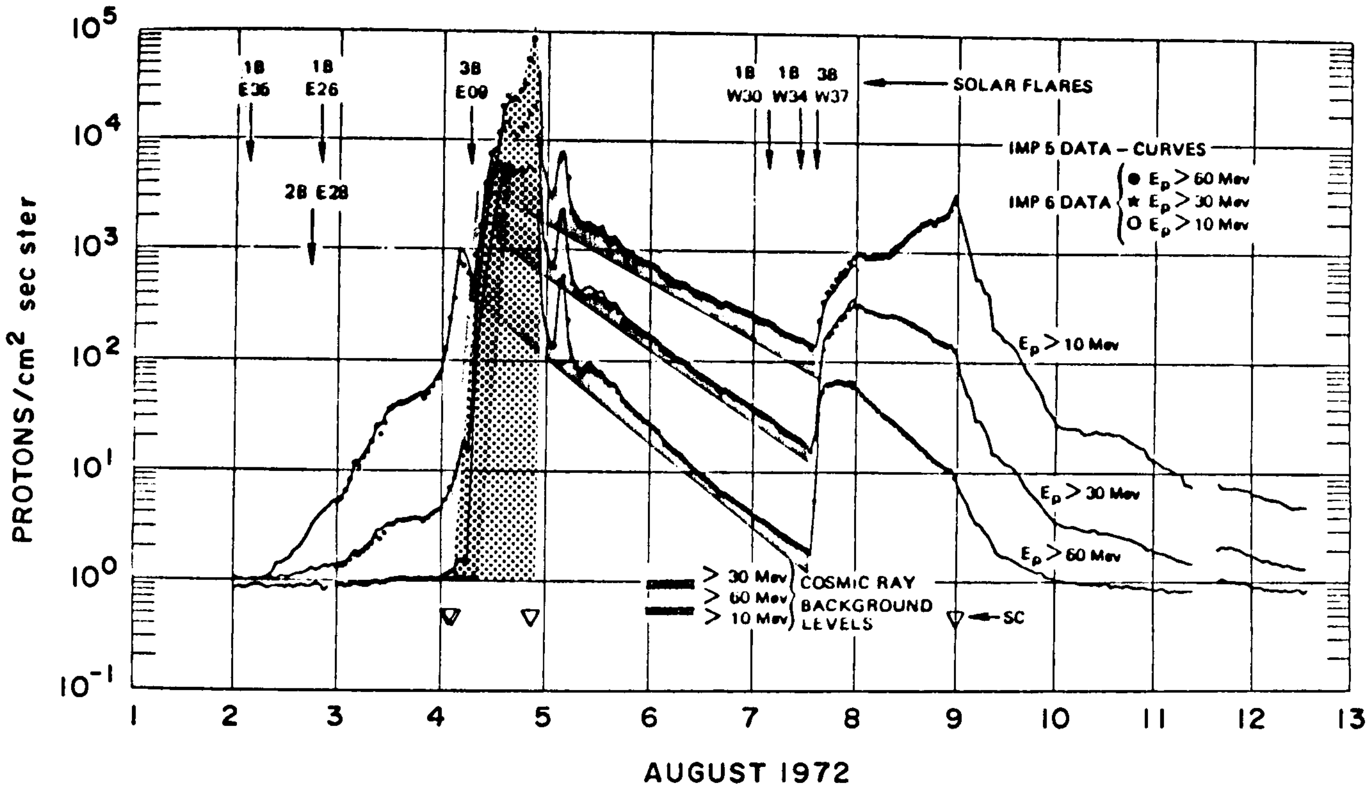

Figure 6. The solar proton time-intensity profile observed for the August 1972 sequence of events. Note the extraordinary hard spectrum and high flux during the time when the earth was between the two converging interplanetary shocks (the second shock overtaking the first).

Table 1. Normalized Elemental Abundances of Solar Energetic Particle Events

NORMALIZED SOLAR ENERGETIC PARTICLE ABUNDANCES

		Adams Mason (1980)		Gloeckler (1979)		Cook et al. (1984)		McGuire et al. (1986)	
		1 MeV		1-20 MeV		10 MeV		6.7-15 MeV	
1	H	1.0		1.0		1.0		1.0	
2	He	2.2	E-2	1.5	E-2			1.5	E-2
3	Li			1.0	E-7	4.8	E-8	2.8	E-6
4	Be			1.5	E-7	6.0	E-9	1.4	E-7
5	B			1.5	E-7	1.2	E-8	1.4	E-7
6	C	1.6	E-4	1.2	E-4	9.6	E-5	1.3	E-4
7	N	3.8	E-5	2.8	E-5	2.7	E-5	3.7	E-5
8	O	3.2	E-4	2.2	E-4	2.2	E-4	2.8	E-4
9	F			4.3	E-7	1.0	E-8	1.4	E-7
10	Ne	5.1	E-5	3.5	E-5	3.1	E-5	3.6	E-5
11	Na	1.6	E-6	3.5	E-6	2.6	E-6	2.4	E-6
12	Mg	4.8	E-5	3.9	E-5	4.3	E-5	5.2	E-5
13	Al	3.5	E-6	3.5	E-6	3.1	E-6	3.3	E-6
14	Si	3.8	E-5	2.8	E-5	3.5	E-5	4.2	E-5
15	P	2.3	E-7	4.3	E-7	1.7	E-7	4.0	E-7
16	S	1.8	E-5	5.7	E-6	7.8	E-6	6.5	E-6
17	Cl	1.7	E-7			7.1	E-8		
18	Ar	3.9	E-6	8.7	E-7	7.3	E-7	4.6	E-6
19	K	1.3	E-7			1.0	E-7		
20	Ca	2.3	E-6	2.6	E-6	3.1	E-6	3.2	E-6
21	Sc					7.8	E-9		
22	Ti	1.0	E-7			1.2	E-7		
23	V					1.2	E-8		
24	Cr	5.7	E-7			5.0	E-7		
25	Mn	4.2	E-7			1.8	E-7		
26	Fe	4.1	E-5	3.3	E-5	3.4	E-5		
27	Co	1.0	E-7			4.8	E-7		
28	Ni	2.2	E-6			1.2	E-6		
29						1.4	E-8		
30						3.8	E-8		

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